PUBLIC INTEREST ENERGY RESEARCH PROGRAM

Renewable Energy: Photovoltaic-Generated Electricity

2001-2011

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Acknowledgement

The authors of this R&D plan gratefully acknowledge the technical support of Art Soinski, Arnold Ward. Comments provided by other Commission staff and solar and photovoltaic colleagues are deeply appreciated. Also appreciated are photovoltaic experts from Sandia James Gee, EPRI Terry Peterson, Siemens Dr. Robert Gay, Chet Farris, REDI Keith Rutledge, Home Power Magazine Richard Perez, SMUD Don Osborne and Vince Schwent and from PV News Paul Maycock.

Disclaimer

DRAFT for PIER Renewables PV RD&D
Today's Date 23 October, 2002
by Joseph McCabe

I. Description of Photovoltaic Energy Technology

A. Electricity from photovoltaics as an energy resource

Photovoltaic (PV) devices, commonly called solar cells or modules, use semiconductor material to directly convert sunlight into electricity. PV is a direct energy conversion device that works when a photon excites a loosely held electron, which is freed and then collected in the solar cell. Channeling these electrons into wires enables them to generate electricity. The electron is returned to the cell, and available to repeat the process indefinitely.

PV power is silent, reliable, has no moving parts, creates no atmospheric air or water pollution, and has very low operation and maintenance costs. Systems are modular, flexible, easily installed, and are applicable wherever there is sunlight. PVs are used to directly power remote residences, satellites, highway traffic and information signs, water pumps, communications stations, navigation buoys, street lights, calculators and many more devices. PVs are well suited for providing power at times when grid power is highly valued, during hot, sunny days.

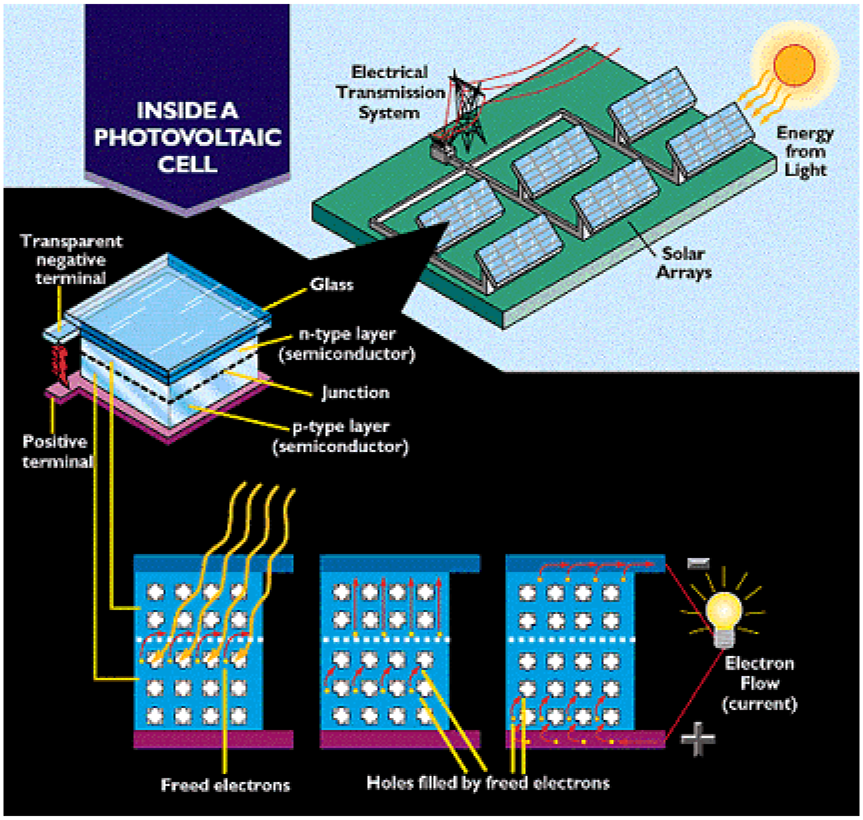

Figure 1: PV Cells Photo-electric effect (Image courtesy of NREL)

Initial costs of PVs are high; however, their expected 20 to 30 years of operation can justify the large expense. In some cases, PVs are very cost effective, because of the value provided beyond alternatives. Many opportunities exist in research, development and demonstration of PV technologies, which will accelerate the cost effectiveness of electricity from PVs.

An area of 100 square miles (10 miles by 10 miles) covered in PVs will produce one half of California's peak demand for electricity, or 25,000 MW of power. A goal for PV is to produce efficient, affordable, reliable systems that can integrate seamlessly into our society. PIER Renewables RD&D hopes to accelerate this vision for the state of California.

1. History of PV

The photovoltaic effect was first recorded by French physicist Edmund Becquerel, in 1839, when he noted the appearance of a voltage when illuminating two identical electrodes in a weak conducting solution. Becquerel's research was investigated and extended by many including, Werner Siemens, the founder of the multinational company Siemens, now a leader in the PV industry with manufacturing facilities in California. The first practical PV cells were made out of crystalline silicon in 1954 by Bell Laboratories in the United States.

Solar electricity came out of the laboratory and was sent into space. In 1958, PV systems found their first major use as a power supply on the Vanguard I satellite. PV units for space were designed to be efficient, reliable, lightweight, and durable. Although very expensive, these PV power supplies were the most cost-effective means of producing electricity for satellites. Today, solar cells power virtually all satellites.

Because the cost of PV was high for anything but specialized and remote applications, limited use of PV occurred throughout the 1960s and early 1970s. Later, the oil crises of the 1970s led to the establishment of a federal PV program for technology development.

Overtime, other applications of PVs have become cost effective, capitalizing on the ability of PVs to produce high quality electricity far away from conventional power grids. Affordable applications include powering telecommunication repeater stations, water pumping, navigational buoys, cathodic protection, lighting for solar home systems, and charging recreational vehicles. The success of the California emergency call box program SAFE (Service Authority for Freeway Emergencies) attests to PV's value in powering dedicated off-grid applications.

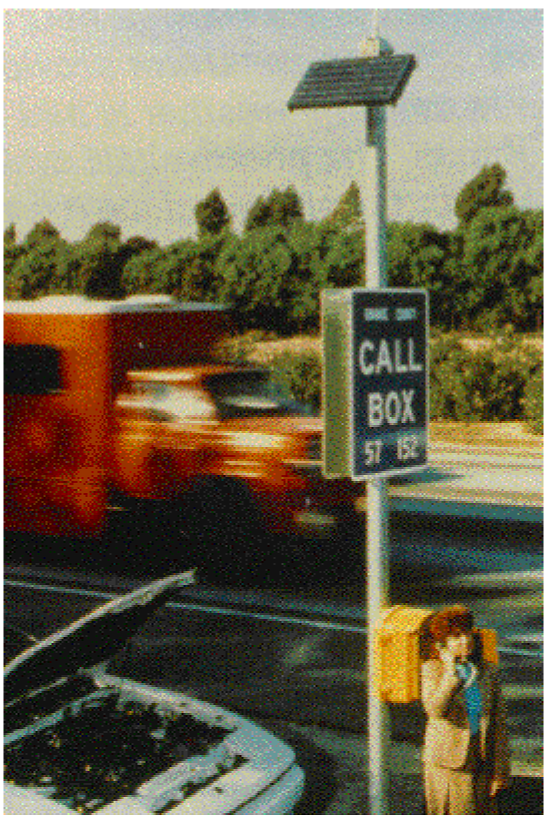

Figure 2: SAFE Callbox

B. Photovoltaic Equipment

1. Cells, Modules, Arrays

Crystalline silicon cells are made from pure silicon sand. Silicon feedstock is manufactured into silicon crystals, cut into wafers which are processed into cells, connected, and packaged into modules. Cells connected together make up a module, which when connected with other modules make up an array. Cells are connected in parallel to increase the current, or in series to increase the current, or in combinations of the two to produce a variety of array voltages and currents. Thin film cells are similar to crystalline cells, except the material can be deposited directly onto a substrate, typically glass. Various cell technology theoretical solar-to-electric efficiencies are reflected in Figure 4. Theoretical efficiencies vary for different semiconductor materials.

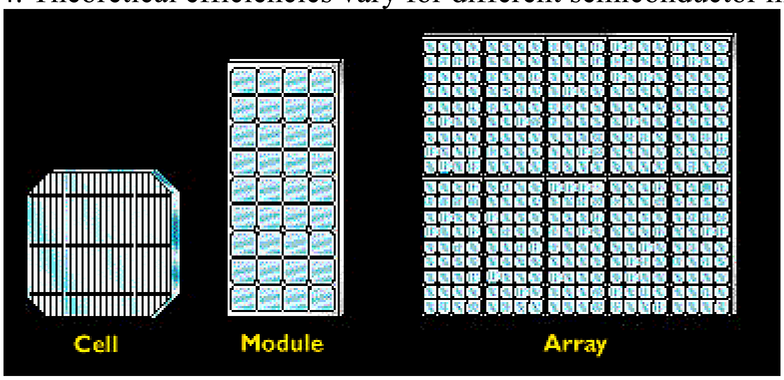

Figure 3: Cells to Module to Array

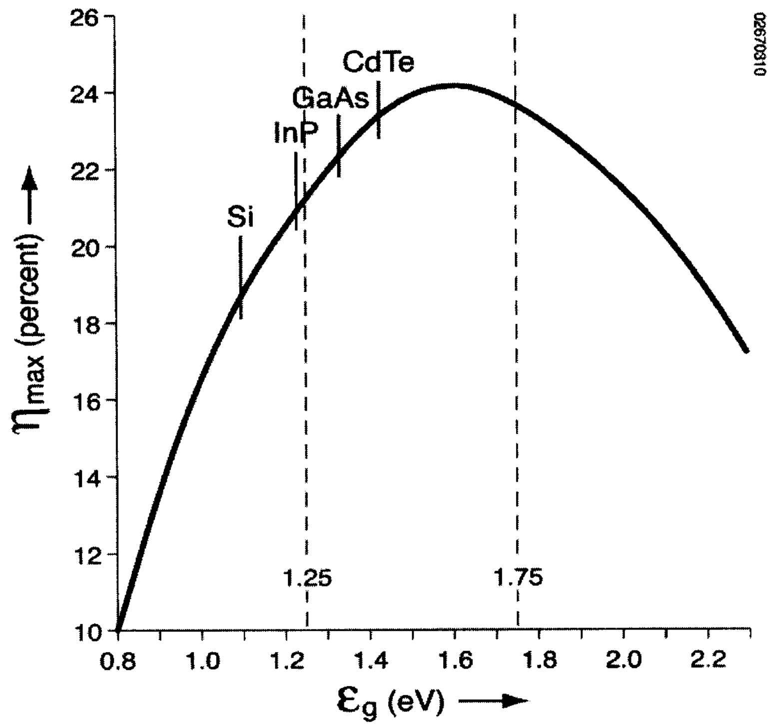

Fig. 11.5. Calculated solar cell efficiency for different bandgap semiconductors.

Figure 4: Theoretical Potential Efficiencies of PV Cells

1. Crystalline (Si, mono and polycrystalline)
Single crystalline silicon wafers, the substrate for integrated circuit (IC) chips, are the substrate for a majority of PV cells. Reject wafers from the IC industry are used by many PV cell manufacturers. 37% of international PV manufacturing is monocrystalline.

Polycrystalline wafers, while lower in efficiency, are easier to manufacture than single crystal wafers. Cast polycrystalline silicon (MC-Si) accounts for nearly 50% of the Si-based solar cells manufactured worldwide. Cell efficiencies of 18.2% have been achieved in large-grained poly-Si ingots.

2. Thin Films (aSi, CIS, CdTe,)
Thin films have an advantage over other technologies because the cell interconnections can be made during the automated deposition process, reducing handling and labor costs. They also use very few materials, and thus cost less to manufacture. Thin films can be deposited on glass, stainless steel, and flexible electrically insolating materials like Kepton. The current disadvantage of thin film compared with crystalline silicon is lower solar-to-electric efficiencies.

a. a-SI Amorphous Silicon Thin-Film Solar Cells
Among the thin-film PV technologies, hydrogenated amorphous silicon (a-Si:H) is one of the most promising options for low-cost solar cells. The technology of a-Si:H for PV is based on two types of device design: single-junction and multiple-junction p-i-n structures. Although major progress has been made in recent years in improving the deposition processes, material quality, device design, and manufacturing processes, the of cell efficiency still needs improvement. It is generally recognized that any significant increase in efficiency can be achieved by using multijunction devices. It is indeed the case as shown by the achievement of a world-record stable efficiency of 13% (initial efficiency of 14.6%) in a triple-junction structure. In an effort to improve the efficiency, stability, and structural properties of a-Si thin films, a new class of material-- hydrogenated microcrystalline silicon-- is emerging as a contender for PV applications. 9.6% of international PV manufacturing is a-Si.

b. CIS Thin-Film Copper Indium Gallium Diselenide (CIGS)
Cu(In,Ga)Se2(CIGS) is one of the most promising material for thin-film PV devices. Recently, a record efficiency of 18.8% has been achieved in a typical device structure consisting of glass/Mo/CIGS/CdS/ZnO fabricated by the physical vapor deposition (PVD) technique. This achievement was made possible by optimization of the optical, electrical, and structural properties of CIGS absorber layer and appropriate design and control of the component layers and their interfaces under different growth conditions. The deposition of a high-quality CIGS absorber layer is the crucial processing step and thus far, the PVD technique appears to be the preferred method. A wide variety of techniques, such as sputtering, spray pyrolysis, closed-space sublimation (CSS), molecular-beam epitaxy (MBE), and electrodeposition, are currently being pursued. Among these, electrodeposition and electroless deposition offer a low-cost option for fabricating. Recently, 15.4%- and 12.4%-efficient thin-film CIGS-based PV devices have been fabricated from solution-based electrodeposited and electroless-deposited precursors. Waste materials can be 30% of the total used materials.

c. CdTe
Enormous progress has been made in recent years on CdTe/CdS thin-film solar cells in which CdTe is the p-type absorber material. The optimum bandgap (1.44 eV) and high absorption coefficient due to direct optical transition make it an ideal PV material with theoretical efficiency of 30%. One of the major advantages of CdTe/CdS thin-film solar cells is the opportunity for low-cost fabrication. A number of relatively simple, low-cost methods have been used to fabricate solar cells with efficiencies in the 10% range. Some of the low-cost deposition methods that show promise include (1) closed-space sublimation, (2) spray deposition, (3) electrodeposition, (4) screen printing, and (5) sputtering. All of these techniques are being considered for large-scale manufacturing by several industries. Most recently, a record 16% efficiency has been reported in a CdS (0.4-µm)/CdTe (3.5-µm) thin-film solar cell in which CdS and CdTe films are deposited by metal-organic CVD deposition (MOCVD) and CSS techniques, respectively. Currently available 10% efficient laminents are being marketed in large quantities for $2 a watt.

3. Polymer, dyes, NASA
A new type of PV cell based on the dye-sensitization of thin (10-20µm) nanocrystalline films of TiO2 in contact with a non-aqueous electrolyte has received a great deal of attention worldwide. The cell is very simple to fabricate and, in principle, its color can be tuned through the visible spectrum, ranging from being completely transparent to black opaque by changing the absorption characteristics of the dye. The highest present efficiency of the dye-sensitized photochemical solar cell is about 11%. The cell has the potential to be a low-cost PV option. Unique applications include PV power and photoelectrochromic windows.

4. High Efficiency / NASA
The tandem combination of a GaInP2 (Eg = 1.9 eV) and GaAs has a theoretical efficiency of ~36%. The most exciting development in recent years has been the fabrication of a high-efficiency (29.5%) monolithic tandem cell consisting of GaInP2 (top cell) and GaAs (bottom cell) with a low-resistivity tunnel-junction interconnect. By virtue of its superior radiation resistance, these cells are now being produced on a large scale for space applications.

5. Other Technologies
PV can be manufactured from any compound where the ratio of valence electrons to atoms is 4, as in the case for group IV elements like silicon. Many materials remain undiscovered, which holds promise for future technology advancements in producing electricity from semiconductors. New advancements in laboratory record efficiencies for thin films continue at a rate of approximately 1/2% per year. See Figure 5 for the historical annual improvements.

RD&D opportunities exist to increase utilization of thin film materials, reduce manufacturing wastes, while reliably increasing module solar to electric efficiencies.

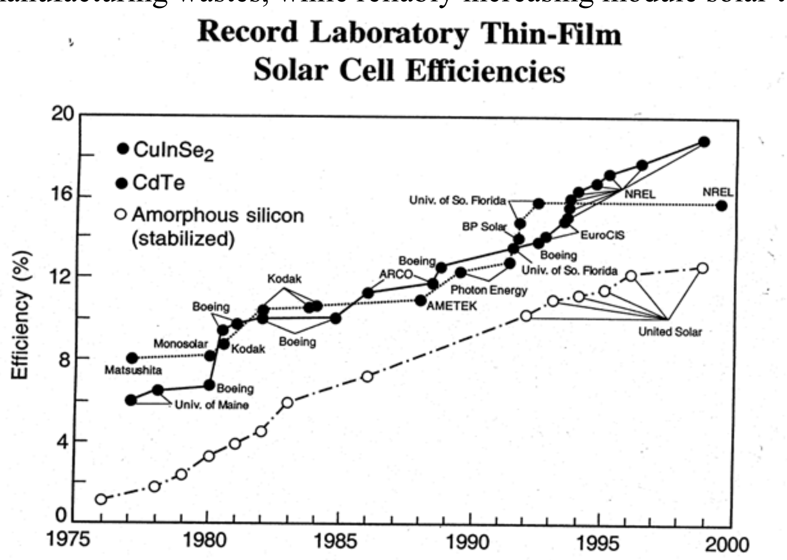

Figure 5: Historical Cell Efficiency improvements

2. Types of Systems

1. Flat plate

Stationary structures are usually used with flat-plate systems typically pointing toward the equator. These structures generally tilt the PV array at a fixed angle that is determined by the latitude of the site, the requirements of the load, and the availability of the sunshine.

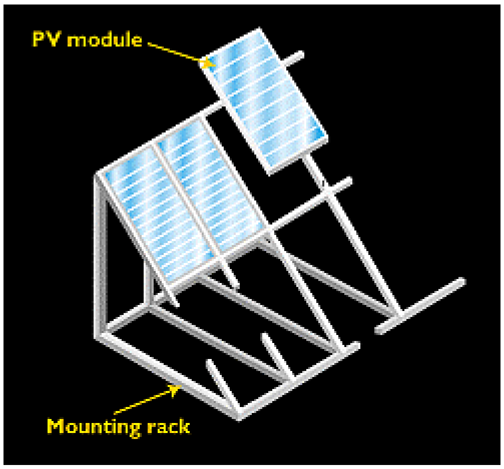

Figure 6: Module Mounting

2. Concentrators

One way to improve energy production from PVs is to employ concentrating optics, which gather sunlight with lenses, thereby increasing the intensity of sunlight striking the PV cell. This is similar to using a magnifying glass.

The primary reason for using concentrators is to decrease the area of solar cell material being used in a system because solar cells are an expensive component of a PV system, on a per-area basis. A concentrator uses relatively inexpensive materials (plastic lenses, metal housings, etc.) to capture a large area of solar energy and focus it onto a small area, where the smaller solar cell resides. One measure of the effectiveness of this approach is the concentration ratio, a measurement of how much concentration the cell is receiving.

Concentrating optics are significantly more expensive than the simple covers needed for flat-plate modules, and most concentrators must track the sun throughout the day and year to be effective. Thus, higher concentration ratios mean using not only expensive tracking mechanisms but also more precise controls than stationary flat-plate systems. High concentration ratios are a particular problem, because the operating temperature of cells increases when excess radiation is concentrated. Cell efficiencies decrease as temperatures increase, and higher temperatures also threaten the long-term stability of PV cells. Therefore, PV cells used in concentrators must be kept cool. RD&D opportunities exist to capture the thermal energy from PV systems, providing cooling for the cells and thermal energy for use.

Transparent glazing using concentrating holograms have the potential of concentrating beam solar energy on PV cells, while allowing diffuse light to be transmitted.

RD&D opportunities exist to integrate concentrating PV collectors into grid connected systems in reliable, multi-beneficial functioning products. Shading value and thermal energy can be obtained from such advanced concentrating systems.

3. Trackers
Up to 40% more power can be obtained by tracking the sun, but trackers are not completely reliable, are more complexity and costly. There are two types of tracking structures: one-axis and two-axis. Single-axis trackers are typically designed to track the sun from east to west on its daily route. They are used with flat-plate systems and some concentrator systems. The two-axis type is primarily used for PV concentrator systems. These systems track not only the sun's daily course but also its seasonal course between the northern and southern hemispheres. Naturally, the more sophisticated the system the more expensive and the more maintenance it may require.

Manual trackers, those rotated by hand, offer more simple structures, and can be positioned at a fixed tilt and azimuth if not being attended.

In the past, many inventions have concentrated on trackers, with little payback. RD&D opportunities exist for trackers to maximize the value of energy produced by PVs, enabling PV energy to match the grid peak energy needs.

4. Building Integration
Building integrated PV, or BIPV, eliminates the need for a packaged collector. Instead, BIPV attempts to replicate a conventional building element, with a surface consisting of PV. Ideally, the façade integrates seamlessly into the building trades, and is aesthetically pleasing to designers and owners. Thus, BIPV, which is discussed in detail in section III-C, eliminates the need for a dedicated structure to hold the modules.

3. Balance of System

In a photovoltaic system, the term 'balance of system' (BOS) refers to all of the system components except the PV modules. These components frequently account for half of the system cost and, unfortunately, most of the system maintenance. The components consist of structures, enclosures, wiring, switchgear, fuses, ground fault detectors, charge controllers, batteries, and inverters. Of these, ground fault detectors, charge controllers, batteries, and inverters are the components that could benefit most from developments in both technology and understanding.

Connecting a photovoltaic system to the grid requires an inverter that is specially designed to be safe and efficient. Inverters, used in grid connected PV systems, eliminate many problems previously encountered with battery storage.
(http://www.sandia.gov/pv/bos.htm)

1. Structures
Structures that hold PV are necessary to secure the investment. RD&D opportunities exist to develop seamless integration of PV into conventional building practices. Sacramento

Municipal Utility District (SMUD's) experience of 1.3% roof leaks highlights that roof mounted systems can benefit from technological advancements which make installation simpler, and make roofing penetrations fewer and more reliable.

2. Charge Controllers
Charge controllers optimize the energy storage in batteries from PV systems. Batteries have the ability to dispatch energy at specific times, thus making this energy more flexible and valuable to a grid tied system. In addition, a PV system with batteries can be operated as an un-interruptible power supply (UPS), adding more value to the PV generated electricity. RD&D opportunities exist to develop sophisticated charge controlling systems, which integrate into other energy management and grid interacting inverters.

3. Inverters
Inverters are needed to convert direct current (DC) to alternating current (AC) typically used by appliances and the utility grid. Inverters specifically designed for PV systems allow for the fluctuating nature of the DC power voltage and currents due to changes in sunlight intensity and cell temperatures. The goal of these inverters is to safely, reliably and efficiently obtain the maximum power available from the PV system and convert it to AC. Grid interactive inverters allow PV-produced electricity to be supplied to the AC electric grid. These inverters must be responsive to changing grid activities including power transients due to near-by lightning, switching transients, voltage notches, sags, and swells. The grid interactive inverter must not:

- Island (put energy back into the grid when the grid is down)
- Emit excessive levels of radio frequency interference
- Have excessive total harmonic distortion
- Interfere with other utility customers.

In a 1997 study 75% of PV system problems were attributed to inverters (SNL/NREL PV System Reliability Workshop 1997). Having to repair or replace an inverter could erase all economic advantages of a cost-competitive PV system. Research, development and demonstration opportunities exist to integrate the latest high-performance power converter technologies into complete PV systems for overall system efficiency and cost improvements. Advanced Insulated Gate Bipolar Transistors (IGBT) technology holds promise for up to 99% efficient energy conversion.

Module scale inverters (MSIs), or Micro-inverters, are mounted directly to the back of a module, eliminating the need for DC distribution lines, DC disconnects, and DC over-current protection. Complete PV modules with micro-inverters are sometimes called AC Modules. Such systems are easily deployed, because they are more modular and flexibly meet increasing energy requirements.

Inverters are also designed to operate if a grid is down, in which case the PV system is considered an un-interruptible power supply (UPS). UPS has enormous value to grid connected energy users who cannot afford to be without electrical power.

A PV powered UPS has many components similar to a grid independent system. Grid independent PV systems have been used for decades in developing nations, for telecommunications and for remote sites. While very similar to grid tied, grid independent systems include independent energy storage, such as batteries, and a system to manage the energy storage, a charge controller.

Inverters are a week link in PV systems, reflected in the short warranty period. While PV modules can have 20-and 30-year warranties, inverters typically have three-year warranties. System reliability will be improved with attention to long term reliability of this system component. Highly accelerated testing (HALTS^{sm}) during extreme temperatures can help improve reliability. RD&D efforts should include reducing components with limited lifetimes, reliably eliminating the need for transformers, and having reliability so high that monitoring and external controls become unnecessary. An inverter which serves the PV, fuel cell, uninterruptible power supply (UPS), automotive and home inverter markets would have reduced costs and increased reliability due to mass production. RD&D opportunities exist to develop reliable, cost-effective grid interactive inverter systems with long warranties (10 years and longer), increased inverter availability and reduced inverter nuisance trips, which maximize the value of energy generated from PV systems.

4. Metering

Metering of PV systems helps to ensure proper operation of the system, and encourages the research and development of properly installed components. Additionally, time of use (TOU) metering can improve the economics of PV systems by giving a credit for the high value times when PV produces electricity. TOU meters help encourage electricity consumers to become "customer-generators", thereby reducing loads on the electricity grid and contributing generating capacity during peak demand periods. RD&D opportunities exist for advancement in equipment and technologies to improve metering in PV systems.

5. Complete Systems

Many cells make a module, many modules make arrays, and many arrays -- combined with power conditioning, wiring, and mounting structures -- make large systems. Large systems can be flat plate, tracking or concentrators. When considering solar-to-electric efficiency, the goal is to increase total system efficiency. Each electrical component adds (or subtracts) to the total system energy efficiency. Similarly, with economics, module costs are only a part of the total system costs of PV electricity. It is important to know the difference between cell efficiencies, module efficiencies and system efficiencies, as well as their respective costs.

For example, if a module has a sunlight-to-electrical efficiency of 10%, and the rest of the system has an 80% efficiency (10% inverter losses, 10% losses due to wiring and mismatch losses), then the PV system efficiency is 8% (10%* 80%).

RD&D Opportunities for Photovoltaic Systems

RD&D opportunities exist to diligently address all efficiency components and increase the total energy provided by a PV system. Sizing of balance of systems components can have a dramatic effect on system performance and system costs. RD&D opportunities exist to closely match the PV system output to inverter size and peak performance. RD&D opportunities exist to develop cost effective wire sizing, appropriate to the high value of electricity from PV systems. Reduction of mean time between failures for balance of systems components and increased availability of system power should be a goal of all RD&D efforts. As PV module prices decrease the BOS costs and associated RD&D activities become increasingly important in overall system affordability.

A 1996 chart of various components and total systems costs for 1 kW are reflected in Figure 7. The figure shows three different types of systems: flat plate, single axis, and double axis tracking for both Florida and California.

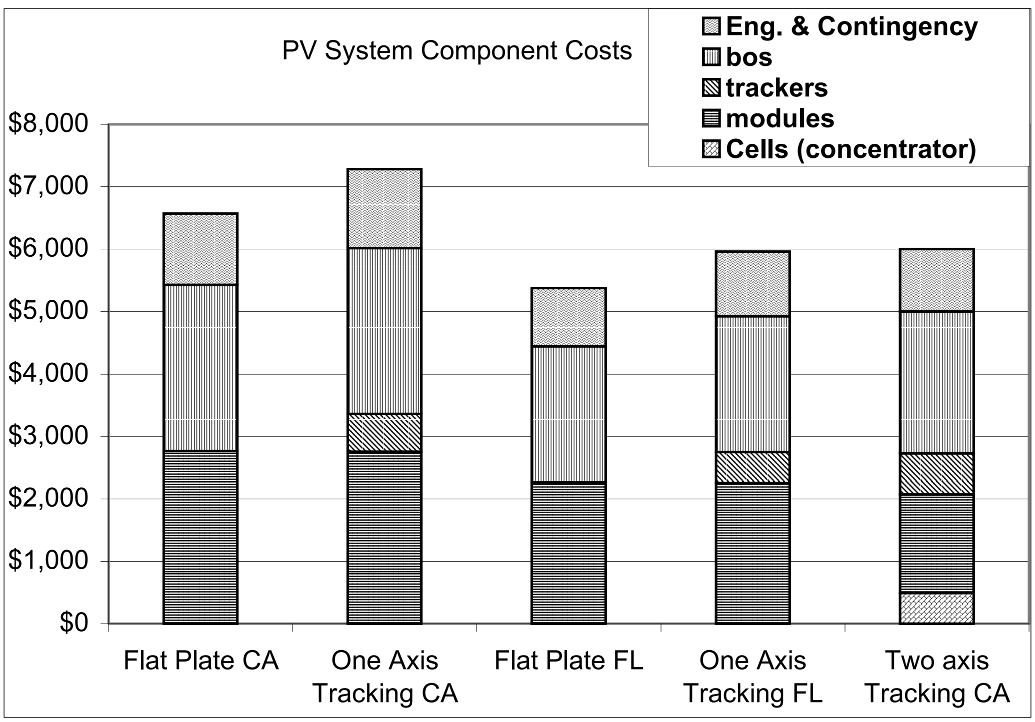

Figure 7: Stacked Bar Chart Component Costs flat plates vs. tracking vs. concentrators